Extreme Ultraviolet Interferometry

by

Kenneth Alan Goldberg

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Committee in charge:

Professor Roger W. Falcone, Chair
Professor Jeffrey Bokor
Professor Joseph Orenstein

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Abstract

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EUV lithography is a promising and viable candidate for circuit fabrication with 0.1-micron critical dimension and smaller. In order to achieve diffraction-limited performance, all-reflective multilayer-coated lithographic imaging systems operating near 13-nm wavelength and 0.1 NA have system wavefront tolerances of 0.27 nm, or 0.02 waves RMS. Owing to the highly-sensitive resonant reflective properties of multilayer mirrors and extraordinarily tight tolerances set forth for their fabrication, EUV optical systems require at-wavelength EUV interferometry for final alignment and qualification.

This dissertation discusses the development and successful implementation of high-accuracy EUV interferometric techniques. Proof-of-principle experiments with a prototype EUV point-diffraction interferometer for the measurement of Fresnel zoneplate lenses first demonstrated sub-wavelength EUV interferometric capability. These experiments spurred the development of the superior phase-shifting point-diffraction interferometer (PS/PDI), which has been implemented for the testing of an all-reflective lithographic-quality EUV optical system. Both systems rely on pinhole diffraction to produce spherical reference wavefronts in a common-path geometry. Extensive experiments demonstrate EUV wavefront-measuring precision beyond 0.02 waves RMS. EUV imaging experiments provide verification of the high-accuracy of the point-diffraction principle, and demonstrate the utility of the measurements in successfully predicting imaging performance.

Complementary to the experimental research, several areas of theoretical investigation related to the novel PS/PDI system are presented. First-principles electromagnetic field simulations of pinhole diffraction are conducted to ascertain the upper limits of measurement accuracy and to guide selection of the pinhole diameter. Investigations of the relative merits of different PS/PDI configurations accompany a general study of the most significant sources of systematic measurement errors.

To overcome a variety of experimental difficulties, several new methods in interferogram analysis and phase-retrieval were developed: the Fourier-Transform Method of Phase-Shift Determination, which uses Fourier-domain analysis to improve the accuracy of phase-shifting interferometry; the Fourier-

Transform Guided Unwrap Method, which was developed to overcome difficulties associated with a high density of mid-spatial-frequency blemishes and which uses a low-spatial-frequency approximation to the measured wavefront to guide the phase unwrapping in the presence of noise; and, finally, an expedient method of Gram-Schmidt orthogonalization which facilitates polynomial basis transformations in wave-front surface fitting procedures.

Dedicated to Hector Medecki, my teacher, mentor, and inspiration.
With deeper understanding than I shall ever have, he intuits light.

Table of Contents

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It is beyond argument that the successes of this project would never have been realized were it not for the creative vision and sincere dedication of Hector Medecki, the primary inventor of the phase-shifting point-diffraction interferometer, the *Medecki Interferometer*, whose clever and insightful approach daily brings the joy of experimental research to light.

The ingenuity of Chief Engineer Philip Batson and his team, including Drew Kemp and Senajith Rekawa, is evident in every flexural-pivot, window flange, and high-resolution stage. On a shoestring budget, they designed and built the system to succeed, then re-designed it to excel.

Special acknowledgment must be given to Paul Denham, whose unique electronic and mechanical contributions and tireless efforts play an indispensable role in the facility with which these experiments are performed.

The intuitive and rapid computer interface through which the numerous translational stages are controlled is largely due to the persistence and considerable skill of undergraduate computer scientist Joshua Cantrell. Additional technical computer support essential for the present and continued development and improvement of the experimental interface is provided by Shane Cantrell. Numerous computer and electronic systems were installed and are maintained by Ron Tackeberry, Everett Harvey, and Jos Polman, whose responsive support is greatly appreciated.

The most critical components of the interferometers are the tiny reference pinholes. For their contributions to the fabrication of these essential components, gratitude is due to James Spallas, Ralph Hostetler, Charles Fields, and Richard Livengood. Special thanks are also due to Erik Anderson for his continuing support with pinhole fabrication and other exceptionally challenging tasks, including the fabrication of the high-resolution EUV Fresnel zoneplates used in the first-round of interferometry experiments.

EUV imaging experiments could not have been performed without the skillful contributions of Avijit Ray-Chaudhuri and Kevin Krenz of Sandia National Laboratories.

Two other graduate student researchers working on this project share credit for its every success and deserve recognition for their essential contributions to this team effort: Edita Tejnil, whose often shaky hands were always steady enough to place sub-micron pinholes to within 10 μm of their target; and SangHun Lee, who, as a first-year graduate student faced with a steep learning-curve, met every challenge with enthusiasm.

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Thank You.

Introduction

EUV lithography is a promising and viable candidate for circuit fabrication with 0.1-micron critical dimension and smaller. To achieve this end at 13-nm wavelength, nearly diffraction-limited, multilayer-coated, near-normal-incidence reflective optical systems with 0.1 numerical aperture are required (Himel 1993). The suggested wavefront aberration tolerance for these sophisticated, all-reflective systems, composed of aspherical elements, is only 0.02 waves RMS, or 0.27 nm (Williamson 1994). This places extremely high demands on the fabrication of EUV mirror substrates and multilayer coatings and even higher demands on the metrology tools required to characterize them.

The EUV wavefront is determined by the geometric figure of the mirror surfaces and by the properties of the multilayer coatings, which are deposited across mirror areas of several square centimeters. While advanced visible-light interferometric techniques possessing the required measurement accuracy are being developed (Sommargren 1996a, 1996b), optical aberrations arising from multilayer coating defects and thickness errors are measurable only at the EUV operational wavelength. Furthermore, it is widely agreed in the lithography community that final alignment and qualification must be performed *at-wavelength* in order to successfully predict the imaging performance of an optical system. These factors motivate the development of high-accuracy EUV wavefront-measuring interferometry.

This thesis is devoted to the development of EUV interferometry capable of achieving the highest wavefront-measuring accuracy and precision. Early proof-of-principle experiments with a prototype EUV point-diffraction interferometer (PDI) for the measurement of Fresnel zoneplate lenses (Goldberg 1995a, 1995b) demonstrated sub-wavelength EUV interferometric capability, and revealed the very high quality of the lithographically-fabricated zoneplate optics. Experience and the limitations of the conventional PDI spurred the development of the superior *phase-shifting point-diffraction interferometer* (PS/PDI) (Medecki et al. 1996). The implementation and development of this novel tool at EUV wavelengths is now in progress on an undulator beamline at Ernest Orlando Lawrence Berkeley National Laboratory’s Advanced Light Source synchrotron radiation facility (Goldberg et al. 1995b, 1997; Tejnil et al. 1996a, 1997).

The prototype PS/PDI is being used to test lithographic-quality multilayer-coated 10× Schwarzschild objectives. While extensive experiments with one such objective have revealed its nearly diffraction-limited performance, the more important data comprise a wealth of information about the performance of the interferometer itself.

Evaluation of the interferometer's performance has revealed significant progress toward the accuracy and precision targets set by the wavefront measurement requirements of EUV lithography. In tens of separate trials performed on a 0.07 NA sub-aperture of the 10× Schwarzschild objective, a wavefront-measuring precision better than 0.02 waves (0.27 nm, or $\lambda/50$) has been observed. Accuracy verification with imaging experiments has shown excellent agreement between predicted and measured performance. Additionally, the interferometer has been used in the first direct quantitative measurement of chromatic aberrations related to the isolated properties of multilayer reflective coatings.

Accompanying the discussion of development of the experimental system and its prototypical components, theoretical and empirical investigations of the systematic and random error sources are presented in this thesis. The studies are presented in a very general manner and are intended to serve as a framework for the investigation of the most significant error sources in the PS/PDI measurement of arbitrary optical systems. Special attention is given to the EUV optical systems of interest to this research. The theoretical studies feed back into the experimental methods and have improved the quality and reliability of the measurements.

Experimental difficulties have complicated many aspects if this research, and have necessitated the creation of new general methods of interferogram analysis. Several techniques developed by the author and described herein overcome the limitations of the optical system under test and problems associated with the experimental system. Emphasis is placed on the practical implementation of robust and efficient analysis methods, and many examples of varying complexity are presented.

The investigation of the measurement precision has identified the individual contributions of the interferometer's components to the measurement uncertainties. It appears clear that even with the high performance demonstrated to date, there are several areas in which improvements are possible; and specific recommendations for such are made.

EUV interferometry research and experiments were performed between May 1993 and November 1997 using facilities of the Lawrence Berkeley National Laboratory and the University of California, Berkeley. EUV Imaging experiments were conducted at Sandia National Laboratory, in Livermore, California.

OVERVIEW

This thesis is organized into four main sections, covering both theoretical investigations and the results of experimental research. Part I presents a detailed investigation of the most critical physical component of any point-diffraction interferometer: the pinhole responsible for the point-diffraction that generates the spherical reference wavefront. Here, a highly detailed vector model of the electromagnetic field in the vicinity of the tiny pinholes is illuminated with EUV light and investigated to predict the upper limits of reference wavefront accuracy.

Part II describes the research conducted with an EUV point diffraction interferometer (PDI) used to evaluate the wavefront diffracted by high-resolution Fresnel zoneplate lenses. This research paved the way for the development of the more sophisticated *phase-shifting point diffraction interferometer* (PS/PDI). All of the research related to the EUV PS/PDI is presented in Part III. Chapter 4, which provides a description of several PS/PDI designs, is followed in Chapter 5 by a mathematical investigation of systematic error sources and measurement issues. The interferometer configuration for the measurement of a Schwarzschild objective is described in Chapter 6, and the measurements themselves are presented in Chapter 7. Chapter 8 contains the results of numerous experiments conducted to evaluate the performance of the interferometer. Finally, Chapter 9 records an investigation of chromatic aberrations and the wavelength-dependent behavior of the Schwarzschild objective related to the properties of the multilayer coatings.

The six chapters of Part IV all describe practical aspects of interferogram analysis, including detailed procedural descriptions of the individual methods. Following a general overview in Chapter 10, Chapters 11 and 12 provide a description of the two major classes of phase-recovery methods, single interferogram techniques and multiple interferogram phase-shifting techniques, respectively. Chapter 12 also includes a novel phase-shifting analysis method developed by the author to overcome phase-shift calibration errors, the *Fourier-Transform Method of Phase-Shift Determination*. This method eliminates problems associated with phase-step uncertainties and fringe print-through in situations where it may be applied.

The critically important and challenging subject of phase-unwrapping is addressed in Chapter 13. Here, following a discussion of conventional methods, a new unwrapping procedure developed by the author is described. This method combines highly-filtered phase-information with raw phase data to perform what is called *Fourier-Transform Guided Unwrapping*. This robust method was designed to overcome the presence of numerous invalid data regions found in the measurement of the EUV Schwarzschild objective. It preserves all of the phase information present in the raw *wrapped* phasemap without suffering the complications from invalid points that plague all other unwrapping methods.

Analysis in terms of a convenient set of aberration polynomials, such as the familiar Zernike circle polynomials, is essential for the accurate description and interpretation of the measured data. Chapter 14 describes some important properties of the Zernike polynomials and presents practical issues of how these functions may be most effectively represented on a computer. Chapter 15 describes general methods of wavefront surface fitting, including the very important Gram-Schmidt method of orthogonalization which is extremely useful for minimizing uncertainties associated with polynomial fitting. A modification made by the author to the published method streamlines the fitting procedure and reduces uncertainties by eliminating the need to perform a matrix inversion in the transformation between two polynomial basis sets.

Following the concluding remarks of Chapter 16, the seven appendices cover several auxiliary topics important to this research. These include EUV optical properties, EUV optical systems, EUV multilayer behavior, and Fresnel zoneplate lenses. Also given are the definition of fringe contrast, followed by a Fourier-domain method of fringe contrast determination implemented by the author. Finally, there is a note regarding the conventions used in plotting the coefficients of the Zernike polynomials when representing a wavefront surface.